calculated conductivity; g_i, statistical weight of Na^+ ion; μ_e, electron mobility; μ_i, ion mobility; n_e, n_i, electron and ion concentrations; n_i, g_i', concentration and statistical weight of O_2^- ions; n_a, g_0', concentration and statistical weight of O_2 molecules; affinity of O_2 to an electron; E, electric field strength.

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COMBINED USE OF QUALITATIVE AND QUANTITATIVE REFRACTOMETRIC METHODS

E. V. Gumennik, O. A. Evtikhieva, B. S. Rinkevichyus, and Yu. D. Chashechkin

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The results of an analysis of the operation of multichannel and scanning laser refractometers as well as systems enabling simultaneous employment of schlieren and laser refractometric methods in hydroaerodynamic experiments are presented.

In heat- and mass-transfer problems, studies of the distributions of the density, concentration, temperature, and other parameters, giving rise to the presence of a gradient in the index of refraction, are of great significance. The gradient of the index of refraction can be measured by different optical methods [1, 2], but in experimental practice only three are most widely used: interferometric, schlieren, and direct-schlieren methods.

A convenient quantitative refractometric method in practice is the method based on recording in the form of an electric signal the instantaneous value of the angle of deflection of the probing laser beam [3], which yields operational quantitative information on the local value of the gradient of the quantity under study with high spatial resolution.

Quantitative information on the spatial structure of a nonuniform medium can be obtained with a multichannel laser refractometer, first proposed in [4]. In this case the medium under study is probed with a collection of parallel narrow beams of light and the angles of deflection of all beams are measured simultaneously.

In the study of a wide class of phenomena in hydro- and aerodynamics the simultaneous employment of shadow methods, which give qualitative information about the behavior of the quantity under study in a large spatial volume, and of a laser refractometer, which records local quantitative information, imparts to the measuring system qualitatively new properties, since it enables separating, for carrying out quantitative measurements, the most informative sections of the field under study and visually monitoring the development of the process under study.

To study dynamic phenomena in stratified media we developed and investigated laser refractometers: single-channel, multichannel, scanning, and their combination with the IAB-458 schlieren apparatus.

Institute of Problems in Mechanics, Academy of Sciences of the USSR, Moscow.

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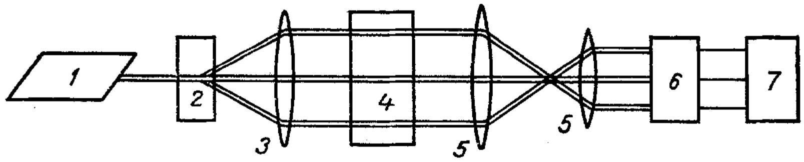

Fig. 1. Structural layout of a multichannel laser refractometer.

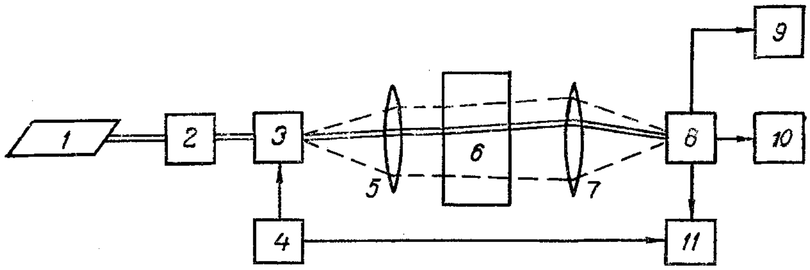

Fig. 2. Structural layout of the laser scanning refractometer (LSR).

Multichannel Laser Refractometer. One possible variant of a multichannel refractometer is shown in Fig. 1. The light beam from the laser 1 passes through a Raman-Nata ultrasonic modulator (USM) 2 and as a result of diffraction by an ultrasonic wave splits into a fan of diverging beams, propagating at different angles to the optic axis. The USM is placed in the focal plane of the lens 3, which converts the fan of diverging beams into a collection of parallel beams. The distance between the beams is changed by changing the frequency of the ultrasonic wave and by selecting the focal length of the lens. The angles of deflection of the beams are measured with a matrix of position-sensitive photodetectors (PSP) 6, the signal from which is recorded on a multichannel automatic plotter or a loop oscillograph 7. An optical system 5, which provides the required distance between the beams incident on the photodetectors, is placed between the medium under study 4 and the matrix. The parameters of the optical system, just as the parameters of the PSP, determine the sensitivity of the refractometer and the range of quantities measured.

Such a refractometer was used to study the axisymmetric nonstationary nonuniformities forming when heat propagates from the heated cylindrical wire into the liquid surrounding it. The radiation source was an LG-52-1 laser, and the collection of eight parallel probing beams was obtained with the help of a Raman-Nata USM, operating at a frequency of 4 MHz. With the use of a lens with a focal length of 50 mm this enabled probing the object under study with a step of 100 μm, which is optimal for nonuniformities with dimensions of about 1 mm. The angles of deflection of the beams were recorded with a straight array of light guides combined with photodiodes, connected pairwise for subtraction. In the experiment angles down to 10^{-5} rad were recorded.

Laser Scanning Refractometer. Operational quantitative information on the spatial structure of the quantity under study was obtained by a method based on the electric recording of the instantaneous value of the refraction of the narrow scanning laser beam [5]. The structural layout of the laser scanning refractometer (LSR), implementing this method, is shown in Fig. 2. The light beam generated by the laser 1 and optimized by the system 2 in order to obtain the best spatial resolution and the highest sensitivity of the system [3] falls on the scanner 3, consisting of a mirror, whose angle of inclination is controlled with the help of an electric signal generated by the generator 4. The scanner 3 lies in the front focal point of the illuminating objective 5, and the angular scanning is thus transformed into plane-parallel scanning of the laser beam. The accuracy with which the scanner 3 is positioned at the focal point of the objective 5 is determined by the requirements imposed on the parallel alignment of the probing laser beams, which depend on the purpose of each specific experiment. The value ~ 1' easily attainable in practice is sufficient for many laboratory experiments. The laser beam passing through the object under study 6 is converted by the objective 7 and falls on the PSP 8, situated in the rear focal point of this objective. With this construction of the system, in order to record information on the field of the distribution of the quantity under study, one four-diode (two-

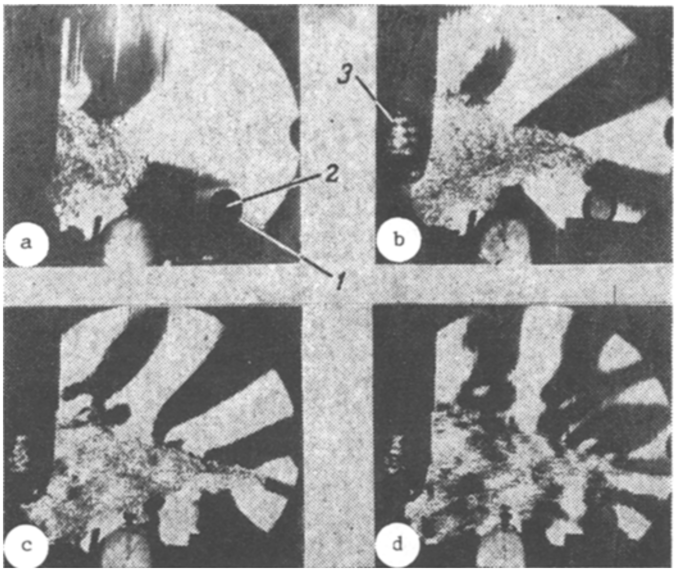

Fig. 3. Schlieren photographs of the evolution of the mixed region inside a stratified liquid ($2\pi/N$ = 5 sec) and of the general pattern of internal waves: 1) semitransparent mirror, with whose help the schlieren apparatus and the laser refractometer are coupled; 2) region of measurements of the laser refractometer; 3) mixer; a) $Nt/2\pi = 0$, b) 1, c) 2, d) 4.4.

coordinate) PSP is used, and the probing laser beam in the case when there is no nonuniformity in the objective 6 remains during scanning immobile on the surface of the PSP with an error determined by the accuracy of the alignment system, aberrations of the optical elements, and vibrations. Information on the measured quantity is recorded with the help of a spectrum analyzer of the parallel type 10 and a voltmeter 9, which is also used for calibrating the PSP. The oscillograph 11 is used for visual monitoring of the alignment of the PSP at the focal point of the objective 7.

The system developed was used to study problems in the hydrodynamics of stratified liquids and gases, in which the distribution of the quantity under study along the vertical coordinate is of greatest interest [6, 7]. For this reason, an oscillographic galvanometer was used as the scanner, allowing scanning along the vertical axis. For large angles of deflection of the mirror α in the dynamic operating range of the scanner the scanning angle 2α is related with the controlling voltage U(t) by the relation

$$\alpha = KU(t),$$

where for a given scanner K is a constant coefficient, determined by the scanner's internal electrical resistance, the properties of the magnetic field in the gap, and the counteracting moment of the braces. Then, the coordinate of the scanning beam Y varies in time according to the law

$$Y(t) = Kf_1U(t),$$

where f_1 is the front focal length of the objective 5 (Fig. 2). Using a symmetrical triangular pulse

$$U(t) = \begin{cases} 2U_0t/T_f, & 0 \leqslant t \leqslant T_f/2, \\ 2U_0(1-t/T_f), & T_f/2 < t < T_f, \end{cases}$$

for controlling the scanner, we obtain probing of the region under study by the laser beam moving with a constant linear velocity

$$v = 2U_0Kf_1/T_f.$$

If the z axis is oriented along the undisturbed beam, then its angular deflection in the yz plane, caused by nonuniformities of the index of refraction present in the region under study, is determined by the expression [1]

$$\theta = \frac{1}{n_0}\int_0^l \frac{\partial n}{\partial y}\,dz. \tag{1}$$

In studying a two-dimensional flow the expression (1) acquires the simple form

$$\theta = \frac{l}{n_0}\frac{\partial n}{\partial y}.$$

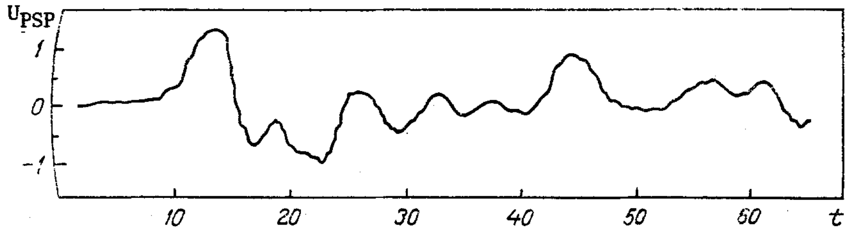

Fig. 4. Internal wave generated with the development of the mixed region inside the stratified liquid ($2\pi/N$ = 5 sec), recorded with the help of the coupled laser refractometer. The amplitude of the internal wave in the region of measurement is proportional to the voltage of the position-sensitive photodetector. U_{PSP}, V; t, sec.

If $T_f \ll \tau$, then the magnitude of the voltage u(t) at the output of the PSP is obtained, in the case of a two-dimensional problem, from the formula

$$u(t) = \frac{Blf_2}{n_0} \frac{\partial n}{\partial y}(Y/v),$$

where the sensitivity of the PSP B is determined by the angle of inclination of the linear section of the direction-finding curve [8], while f_2 is the back focal length of the objective 7 (Fig. 2). The spectrum of the signal u(t) with $T_f \ll \tau$ is adequate for the spatial spectrum of the gradient of the index of refraction along the coordinate Y:

$$F[u(t)] = \frac{Blf_2}{n_0} F\left[\frac{\partial n}{\partial y}(Y/v)\right].$$

The linearity of the dependence of the average frequency of the spectrum of the signal of the LSR, recorded by scanning the object under study, on the scanning velocity v was checked in a test experiment. The average value of the scale of the spatial structure under study is determined from the cotangent of the angle of inclination of the straight line obtained to the horizontal axis.

To monitor the quality of the alignment of the optical system of the LSR, the signal from the output of the PSP 8 was fed while scanning the undisturbed section into the input of the oscillograph 11 (Fig. 2), and the signal from the generator 4, controlling the scanner 3, was used for the external scan. The form of the curve observed on the oscillograph screen can be used to judge the accuracy with which the PSP 8 is aligned on the focal point of the objective 7. The error in the measurement of the angle θ with the help of the system aligned by this method is evaluated using the formula

$$\Delta\theta = \sqrt{\langle u^2 \rangle}/Bf_2, \tag{2}$$

where $\sqrt{\langle u^2 \rangle}$ is the rms value of the voltage of the PSP when probing a uniform region with the scanning beam. The minimum value of the angle Δθ calculated from (2) determines the accuracy of the system when measuring the angle θ and depends on the aberrations of the objectives used, vibrations, laser noise, and the PSP noise. When TAIR-3 objectives were used, aberrations were the most important factor, while the value of Δθ with $B = 2.2 \cdot 10^3$ V/m was less than 5", which is comparable to the highest values achieved in the schlieren method (see [2], p. 25).

Since refractometric methods give information, integrated over the length of the beam, on the measured quantity, the spatial resolution of the laser refractometer is determined by the effect of the following three factors. The first factor is the diffraction divergence of the laser beam, as a result of which the size of the laser beam w(z) at a distance z from the neck is defined as [9]:

$$w^2(z) = w_0^2[1 + (\lambda z/\pi w_0^2)^2].$$

The second factor is the deviation of the probing laser beam at the interface between the object under study and the surrounding medium, because of the fact that the angle of incidence of the probing beam on the interface, owing to errors, cannot be precisely equal to zero. The third factor is the refraction of the probing beam during propagation in the object under study owing to optical nonuniformities of the object. Thus, when a laser beam normally incident on the interface propagates in the medium with a constant gradient of the index of refraction $m = \partial n/\partial y$, the deflection of the beam y from the direction of initial propagation z is determined by the expression [10]

$$y = \frac{n(0)}{m}\left(\mathrm{ch}\,\frac{mz}{n(0)} - 1\right).$$

Depending on the conditions of each specific experiment one of the above-enumerated factors can predominate, and this factor then determines the spatial resolution of the laser refractometer. In the experiments performed with a stratified liquid the spatial resolution was determined by the refraction of the probing beam by optical inhomogeneities of the object under study and constituted 0.5 mm. In this case the diffraction divergence and the error in the angle of incidence on the interface of the media gave the same spatial resolution, equal to 0.2 mm. We note that the analysis of the spatial resolution of the laser refractometer performed above is also valid for a scanning laser refractometer, if $(\tau_d)^{-1} < F$.

Combined Use of a Laser Refractometer and a Schlieren Apparatus. The simultaneous employment of the schlieren and laser refractometric methods was implemented based on an IAB-458 interference-schlieren apparatus and a single-channel laser refractometer. A wide parallel beam of white light, formed by the collimator of the IAB-458 device, illuminates the region of the object under study and falls into the receiving part of the IAB-458, where a shadow pattern is formed with the use of a Foucault knife and can be observed visually with the help of an attachment on the schlieren apparatus and was recorded with the help of a camera. The laser refractometer consists of a laser, an optical system which regulates the parameters and the position of the laser beam within the object under study, position-sensitive photodetectors, and a system for recording information.

The IAB-458 and the laser refractometer were combined with the help of two semitransparent mirrors 1 (Fig. 3a), one of which directs the probing laser beam into the point under study in the object, and the other directs the beam passing through the object onto the PSP. This layout enables coupling the schlieren apparatus not only with a single-channel but also with a multichannel and with scanning refractometers.

The combined use of these two apparatuses in an experiment enables obtaining at the same time information about the object under study: in the entire field of view of the IAB-458 (230 mm in diameter) in the form of a visually observed pattern and in the form of a photograph; in a volume determined by the size of the laser beam (or in the case of the scanning refractometer by the size of the laser beam and type of raster) in the form of an electric signal. In addition, the use of a specially selected filter enables visualizing on the schlieren photograph the region of measurement of the laser refractometer.

In stratified media it is of interest to study the process of evolution of the mixed region inside the stratified liquid [11, 12], the characteristic course of which is determined by the effect of buoyancy forces [6]. The mixed region was created in a 75 × 22 × 70 cm^3 laboratory basin with the help of a special cylindrical mixer 3 (Fig. 3b). The basin was filled by the method of continuous filling [13] with the stratified liquid whose density varied linearly along the vertical coordinate.

Figure 3 shows (in the case of free mixing) the change in the geometric dimensions of the mixed region, which can be seen on the schlieren photographs in the form of a zone of fine-scale structures, and the overall pattern of internal waves generated in this region in the form of white and black bands. Quantitative measurements of the parameters of the internal waves, performed with the help of the coupled laser refractometer, were carried out by making photographs in the known region of the object and the region of the object observed visually on the schlieren pattern. The record of the internal wave at the point 2 obtained in this manner (Fig. 3a) is shown in Fig. 4. In these experiments the period of buoyancy of the medium $2\pi/N$ was equal to 5 sec. The use of a measuring system, consisting of the schlieren apparatus and the laser refractometer coupled with it, in the experiments performed also enabled determining when the reflection of internal waves from the walls of the basin began to affect the development of the process under study (Fig. 3d), whose presence must be taken into account in order to make a correct interpretation of the experimental results obtained and to compare correctly the experimental data and theory.

In conclusion, we note that the problem of obtaining from schlieren photographs quantitative information on the absolute value of the quantity under study is substantially simplified and reduces to performing the relative measurements on them, if the local absolute value of the quantity under study is known at a fixed point of the schlieren pattern. Such information is obtained by coupling the shadow apparatus and a laser refractometer, which can be implemented by modifying the series IAB-451 schlieren apparatus produced commercially, which substantially expands the functional possibilities of these devices.

NOTATION

n_0, index of refraction of the surrounding medium; n, index of refraction; 2α, scanning angle; K, sensitivity based on the voltage of the oscillographic galvanometer; Y, vertical coordinate of the probing laser beam; f_1, f_2, front and back focal length of the objective, U(t), voltage controlled by the scanner, U_0, amplitude of the electrical signal; T_f, frame time; t, running time; v, linear velocity of the scanning laser beam, y and z, Cartesian coordinates; θ, angle of deflection of the probing beam; ℓ, width of the working part; τ, relaxation time of the spatial structure under study; u(t), voltage on the load of the position-sensitive photodetector; B, sensitivity of the PSP; w, transverse size of the laser beam; w_0, size of the laser beam at the neck; λ, wavelength of the laser radiation; n(0), index of refraction of the object under study at the point of entrance of the probing beam; τ_d, time of the element of decomposition; F, upper boundary of the frequency band of the receiving apparatus of the LSR; and N, buoyancy frequency.

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